Effectiveness of Portal Barricades for Underground Storage Magazine

Jae Woon Ahn, So-Young Song

Agency for Defense Development
Yuseong, P.O. Box 35-1, Taejon 305-600, Korea

Abstract

To investigate a new method which can reduce hazard distance by accidental explosion in underground ammunition storage facilities, several hazard reducing devices were reviewed. And the portal barricade in front of the portal was one of the IBD reducing devices studied. To investigate the effectiveness of portal barricades, a series of tests were conducted with concave shape portal barricades. It is found that concave shape portal barricades deflect blast wave exiting from the portal to upward direction, the blast pressures along the extended centerline axis of the tunnel are decreased, and IBD area is similar to a circle centered at the portal. IBD reduction along the centerline axis of the tunnel by the concave shape portal barricades is more than 55%. Airblast reducing effects as a function of side angle, height angle of the portal barricade and stand-off distance from the portal were also analyzed.

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1. Introduction

To investigate a new method which can reduce hazard distance by accidental explosion in underground ammunition storage facilities, several hazard reducing devices were reviewed and tested. One of the hazard reducing devices under consideration was a barricade. Barricade for aboveground magazine is well known as effective means for protecting against fragments, but this provide limited protection against blast. For the underground magazine, a berm in front of the entrance was tested by Klotz club to find its effectiveness against fragment[*]. Test results showed that the berm is effective in decreasing the flow of fragments from the exit at low chamber loading density(3kg/m^3), but the berm can not be treated as a direct obstacle when chamber loading density is relatively high(16kg/m^3). The reason why the berm was not effective in reducing fragments at high chamber loading density can be thought that the berm and its surroundings were not designed properly in shape to catch debris. Our thought on the shape of barricade was as follows. Likewise the debris trap in the underground magazine has a pocket to entrap debris, if a vertical portal barricade is designed to has a concave shape pocket, the barricade may entrap debris from the portal and moreover it may deflect blast wave exiting from the portal to upward direction. To verify our thought on the portal barricade is proper or not, concave shape portal barricades with relatively large dimensions in width and height were tested in small and intermediate scale magazine. Test results showed that concave shape portal barricades are effective in reducing airblast pressure as well as debris. But relatively large size portal barricades may not be economical to be constructed in real underground magazine. Therefore supplementary tests were planned to find out the effect of dimensions of a portal barricade on efficiency. A series of small scale supplementary tests were conducted to prove the effectiveness of the concave shape portal barricades against airblast as a function of side angle, height angle of the portal barricade and stand-off distance from the portal. This paper describes the test and analysis for the large size concave shape portal barricade against airblast and shows the results of the supplementary tests.

[*] Bengt E Vretblat, “Continued Klotz Club Tests”, Fort F-Royal Swedish Fortification Administration

2. Portal barricade tests for airblast mitigation

A portal barricade in front of the tunnel exit was designed in concave shape to catch debris and to deflect airblast to upward direction. Plan and cross sectional view of the tested type I portal barricade is shown in Fig. 1-(a) and Fig. 1-(b) respectively. As can be seen in Fig. 1-(a), the front face of the barricade is vertical and concave in plan. The width of the central wall is the same as the width of the tunnel at the portal, and angled walls on either side form 45 degrees with the extended line of the side wall of the tunnel, and the width of the flat wingwalls on either side is 1.25 times of the width of the tunnel. The angle between edge of the portal barricade and side wall of the tunnel exit is 66 degrees. The height angle, angle between the extended height of the tunnel and the height of the barricade is 20 degrees as shown in Fig. 1-(b). The type I barricade was used in small scale (1/30 scale) and intermediate scale (1/8 scale) tests. In small scale tests, portal barricade was made of 1" thick steel plate. But portal barricades were constructed with reinforced concrete in intermediate scale tests.

A configuration of small scale underground magazine without the type I portal barricade is shown in Fig. 2. The dimension of the steel storage chamber inside of the magazine were L100cm x W50cm x H23cm. A steel pipe with inside diameter of 19.2cm and thickness of 1.25cm was connected to the front steel plate of the chamber acted as access and main tunnel. A debris trap was provided at the end of the access tunnel. The main tunnel intersected an angle of 90 degrees with the access tunnel. The stand-off distance from the exit to the portal barricade was set to the same with the tunnel diameter, 19.2cm. The circles on the main tunnel in Fig. 2 represent side-on pressure gages in the tunnel, Kulite model HKS-375 or XT-190 pressure gages were flush mounted inside of the tunnel.

To measure freefield airblast pressures along the centerline of the tunnel exit, pressure gages were installed along the centerline in the freefield. For off the centerline axis, pressure gages were also installed in direction of 30, 60, 90 degrees horizontal angle from the centerline. 0.4kg and 1.0kg of composition C-4 charges were used as test explosives in small scale tests. Tests were conducted in the same underground magazine as shown in Fig. 2 with portal barricade and without portal barricade. And the effectiveness of portal barricade were analyzed.

Intermediate scale underground magazines were constructed by excavating rock in a mountain in horizontal direction. A test magazine for the test No. T1C3 is shown in Fig. 3. The tested magazine configuration is similar to the small scale one. The overall length of the tunnel was 36m. And the width and height of the tunnel was set to 1.2m. A debris trap was located in front of the test chamber and an angle between the access tunnel and main tunnel was 90 degrees. After testing without a portal barricade, the type I portal barricade was constructed in front of the exit, the stand-off distance between tunnel exit to the portal barricade was set to equal to the tunnel diameter. Second test was conducted in the same chamber with the installed portal barricade. 244kg of composition C-4 explosives were used for both tests.

Fig. 4 shows other intermediate scale magazine configuration for the portal barricade test, this magazine has two exits in opposite direction, and has the type I portal barricade at the exit of right side only. The overall length of the tunnel was about 75m. And the width and height of the exit was set to 1.8m. This test which is called as test No. T5C2 was conducted with 375kg of composition C-4 explosive. Side-on pressures in tunnel for either side of the tunnel, and freefield pressures from the right and left exits were measured. The effectiveness of portal barricade for this magazine configuration can be evaluated in single test.

Comparing the type I barricade dimensions with the exit diameter, overall size of the type I barricade seems relatively large that it is not economical to construct the type I barricade in construction cost point of view. Therefore if effectiveness of the portal barricades as a function of some dimensions is evaluated, portal barricade of economical size can be developed. Small scale magazine configuration which is exactly the same as the one shown in Fig. 2 was used to evaluated the effect of dimensional variations. And sets of small scale portal barricades with different width and height were made to study pressure reducing effects due to variation of portal barricade dimensions. All of the portal barricade dimensional variation tests were conducted with 400g of composition C-4 explosive. Side on pressure gages were installed along the centerline axis of the tunnel to measure freefield pressures. The portal barricades used in these tests were called as the type V, these barricades are concave in shape like the type I, but are lack of flat wingwalls. Plan and cross sectional view of the portal barricade used for the height angle variation test are shown in Fig. 5-(a) and Fig. 5-(b) respectively. As can be seen in Fig. 5, the side angle of the portal barricade was fixed to 20 degrees and height angle was varied from 8.6 to

23 degrees. The stand-off distance was set to the same as the diameter of the tunnel, 19.2cm as shown in Fig. 5-(a).

Portal barricades used to evaluate the dependence of barricade effectiveness on the side angle were similar in shape to the one used in the height angle variation tests. The type V barricades of different side angle but same height angle were made as shown in Fig. 6-(a),(b). The side angle between the barricade edge and side wall of the tunnel exit was 10, 15, 20, 25, 30, 40.9 degrees.

The type I portal barricade shown in Fig. 1 was used to evaluate the effectiveness of barricade on the stand-off distance dependence. If the stand-off distance, the distance from the exit of the tunnel to the portal barricade, varied, both side angle and height angles varied accordingly. The stand-off distance changed from one tunnel diameter (19.2cm) to 2.6 tunnel diameter (50cm), that is, the height angle changed from 11.4 to 20 degrees and the side angle from 40.8 to 66 degrees as shown in Fig. 7.

3. Test results and analysis

It was observed that from the left side exit explosion gas gushed out far along the extended tunnel axis, while from the right side exit it did in the upward direction owing to the portal barricade. It is noted that there is no directional gas flow around the portal barricade except in upward direction.

According to the current U.S. DoD safety standards for underground storage, effective overpressure at the exit, P_w, is expressed as follows,

$$P_w = 895\,(W/V_t)^{0.45}\ , \text{--} \quad (1)$$

where W is the stored explosive weight in pounds, and V_t is the total volume available for gas expansion in ft^3. Freefield overpressure P at distance R from the portal along the tunnel axis can be found,

$$P_w/P = 1.0\,(R/D_t)^{1.35}\ , \text{---} \quad (2)$$

here the tunnel exit diameter, D_t, is a hydraulic diameter which is expressed as 4A/l, where A is the cross sectional area of the tunnel exit, and l is the perimeter of the tunnel exit. According to the current DoD standard, airblast pressure in the freefield is also dependent on the horizontal angle from the tunnel axis, Θ

.

$$P_w/P = 1.0\ (R/D_t)^{1.35}\ [1+(\Theta/56)^2]\ . \text{------------------------------}\quad (3)$$

Fig. 8 shows scaled distance, R/D_t, with respect to the scaled pressure, P_w/P, plot for a small scale test with the type I barricade. Here hollow circles denote data plot for the centerline axis and filled circles, hollow triangles, filled triangles denote data plots for 30, 60 and 90 degrees horizontal angle from the tunnel axis respectively. Solid line designated as "DoD" represents a plot based on eq.(2). Data plot for 30, 60 and 90 degree horizontal angle are not much different from the 0 degree data plot as shown in Fig. 8, and other portal barricade tests show the same tendency. This phenomena can be explained as follows. A portal barricade reflects blast wave to upward direction, the freefield pressures along the tunnel axis are decreased, and the pressures behind the portal are increased. So the hazard area for the blast wave resembles a circle centered at the portal. That means if a portal barricade is installed in front of the exit, airblast pressure in the freefield is independent on the horizontal angle Θ. The scaled blast pressure along the tunnel axis shown in Fig. 8 can be fitted the best by $P_w/P = 5.05\ (R/D_t)^{1.35}$, and in general relationship between scaled pressure vs scaled distance is different from eq.(2) i.e., the coefficient is not 1.0 as eq.(2). Therefore it is better to represent the scaled blast pressure in the freefield as,

$$P_w/P = a_w\ (R/D_t)^{1.35}\ , \text{--}\quad (4)$$

where the coefficient a_w in eq.(4) can be determined from experimental data. And the coefficient a_w depends upon type of the magazine configurations, type of the blast reducing devices, etc. If characteristics of underground magazine with portal barricade and without portal barricade are discriminated by subscript 1, 2 respectively and if R_1, R_2 represent inhabited building distance(IBD) for the magazine 1 and 2, the IBD ratio for magazine 1 based on magazine 2 can be written as,

$$R_1/R_2 = (a_{w2}/a_{w1})^{1/1.35} \text{ . --- } (5)$$

If the coefficient a_{w2} and R_2 are set to 1.0, i.e., IBD for magazine 2 is the same as the DoD criterion, the IBD ratio based on the DoD criteria can be represented by

$$R_1 = (1/a_{w1})^{1/1.35} \text{ . --- } (6)$$

Define IBD reduction (R_1) as '1.0 - IBD ratio'. We then see that the IBD reduction R_1 based on the U.S. DoD standard increases as the coefficient a_{w1} increases.

One of the evaluation methods of airblast reducing effect of the portal barricade is to conduct airblast measurement test in an arbitrary magazine without a portal barricade, do the same test in the same magazine with the portal barricade, and compare two test results of the IBD ratio by eq.(5). The other evaluation method is to predict airblast pressure by eq.(1) and eq.(2) for an arbitrary magazine without portal barricade, in this case a_{w2}=1. Next, conduct a test in the same magazine with a portal barricade, find out the coefficient a_{w1}, and calculate the IBD ratio by eq.(6). The former method represent the IBD reduction by portal barricade based on the test data of no portal barricade, and the latter method represent the IBD reduction based on the current criteria.

Fig. 9-(a), (b) shows the plots of scaled freefield pressure as a function of R/D_t obtained from the small scale test with the explosive weight of 0.4kg and 1.0kg respectively. Here filled circles and hollow circles represent data plot for magazines without the portal barricade and with the type I portal barricade respectively. In Fig. 9-(a), the solid line, at P_w/P = 255, represent the airblast pressure at IBD distance, 1.2 psi. Scaled distances R/D_t at this overpressure level is 49 and 18 for the magazine without the barricade and with the barricade respectively. As shown in the figure, the IBD reduction of this test is about 64%. Fig. 10-(a),(b) shows the intermediate scale test results of the type I portal barricade. The test conditions and the test results are summarized in table 1. The IBD reductions based on no barricade test data are from 55% to 66%, and the IBD reductions based on DoD criteria are from 59% to 70%. The reduction differences

due to the different reference and test scale are not significant. Therefore it is better to use IBD reduction based on DoD criteria because we have to use the current criteria when we want to know IBD for a certain magazine.

Table 1. Test results of Type I portal barricade

Test Scale	Test No.	Chamber loading density (kg/m^3)	a_w		IBD reduction based on no. barr. test data (%)	IBD reduction based on DoD criteria (%)
			Barr	No. Barr		
Small Scale	Test 1	3.5	5.05	1.20	64	70
	Test 2	8.7	3.36	0.9	62	59
Intermediate Scale	T1C3	26.7	4.04	1.39	55	64
	T5C2	21.4	5.13	1.21	66	70

The results of the height variation test with the type V portal barricade were analyzed, and the IBD reductions based on DoD criteria were calculated and compared. The dependence of the a_w upon the height of the portal barricade is shown in Fig. 11. If the height angle is varied from 8.6 to 23 degrees, it seemed that the a_w does not show any dependence on the height angle as shown in this figure.

The results of side angle variation test with the type V portal barricades were analyzed by the same method as in the previous height angle variation tests. The dependence of the a_w upon the side angle is shown in Fig. 12. In the range where the side angle varied from 10.5 to 40.9 degrees, the a_w and IBD reduction increased as the side angle increased. The a_w was given as a function of the side angle, Φ, by

$$a_w = 0.075\,\Phi + 2.12 \;. \quad (7)$$

The IBD reduction can be calculated by eq.(6). Calculated results of the IBD reduction based on DoD criteria along the tunnel axis is varied from 56% to 71%. The IBD reduction is 56% even if the side angle is 10.5 degrees.

Test results of stand-off distance variation with the type I portal barricade are summarized in table 2. In table 2, the side angle 1 refers to the angle that include the width of the wingwalls, and

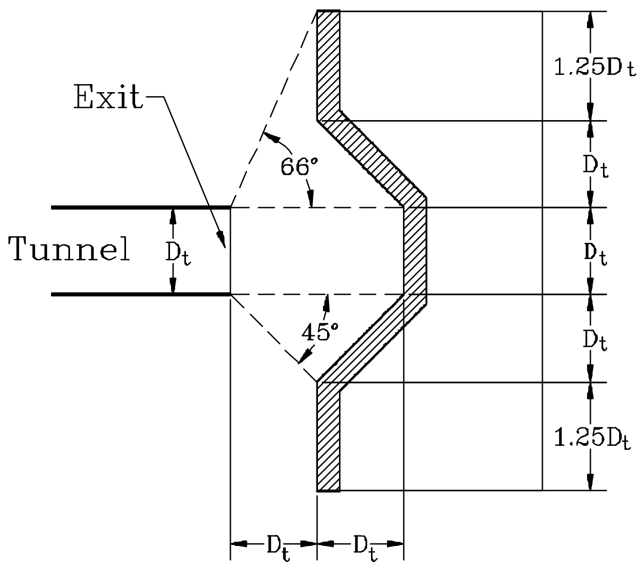
Table 2. Results of stand-off distance variation tests

Stand-off distance (cm)	**Height Angle (deg)**	**Side Angle 1 (deg)**	**Side Angle 2 (deg)**	**a_w**	**IBD reduction based on DoD criteria(%)**
19.2	20	66	45	5.05	70
25.0	17.6	60	38	3.89	63
30.0	15.9	55	33	3.97	64
40.0	13.3	47	26	3.72	62
50.0	11.4	41	21	2.81	53

the side angle 2 refers to the one that count only the concave part of the barricade(ref. Fig. 7). As the stand-off distance varied, the height angle changed from 11.4 to 20 degrees and the side angle 1 from 40.8 to 66 degrees accordingly. Since the height angle did not affect the coefficient a_w with the range from 8.6 to 23 degrees from the results in the height angle variation test, we can neglect the effect of the height angle. So the coefficient a_w can be expressed as a function of the side angle Φ only. Relationship between the side angle 1 versus the a_w is shown in Fig. 13. In this figure, filled circles represent stand off distance variation test data and the line does the fitted result, $a_w = 0.073\ \Phi - 0.06$. Hollow circles represent side angle variation test data from Fig. 12 and the line does the fitted result, $a_w = 0.075\ \Phi + 2.12$, eq.(7). The slope of these two lines are almost same and only intercepts with y axis are different. Therefore, within the stand-off distances of 1 to 2.6 tunnel diameter, the effectiveness of portal barricade depends only on the side angle, and nonlinear propagation of blast wave does not have to be considered. The extra side angles for the flat wingwall for the type I barricade, the difference of angle 1 and angle 2, are about 21 degrees as shown in table 2. In Fig. 13, the side angle difference between two lines at the same a_w value is about 31 degrees. It is our thought that angle difference between 31 and 21 degrees is caused by shape difference between the type I (concave part + flat wing wall) and the type V (only concave part) portal barricade.

4. Conclusions

In summary of test results, the portal barricade reflect blast wave exiting from the portal to upward direction, the pressures along the center line of the exit are decreased and pressures in opposite direction are increased. Hence airblast hazard area resembles a circle centered at the portal. Tested portal barricade is effective in reducing blast hazard and the IBD reductions based on no barricade test data are from 55% to 66%. It is found that the coefficient a_w directly related to the efficiency of the portal barricade. For height angle greater than 8.6 degrees, it seems that the a_w does not have any dependence on the height angle. In the range where side angle varied from 10.5 to 40.9 degrees, the a_w can be expressed as a function of side angle Φ, $a_w = 0.075\ \Phi + 2.12$. For the stand-off distances within 1 to 2.6 tunnel diameter, the effectiveness of a portal barricade depends only on the side angle, and nonlinear propagation of blastwave does not have to be considered. In summary, IBD reduction along the centerline axis is expected to be more than 50% if we install a proper size concave shape portal barricade within proper stand-off distance.



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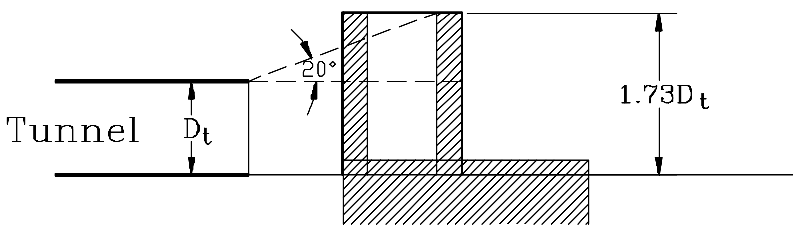


(b)

Fig. 1 Type I portal barricade

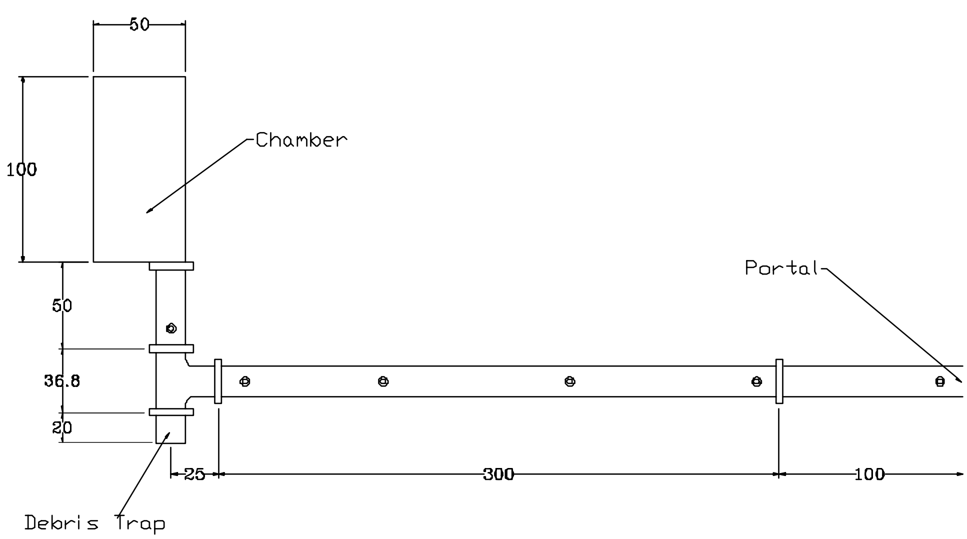


Fig. 2 Small scale test magazine configuration for portal barricade test

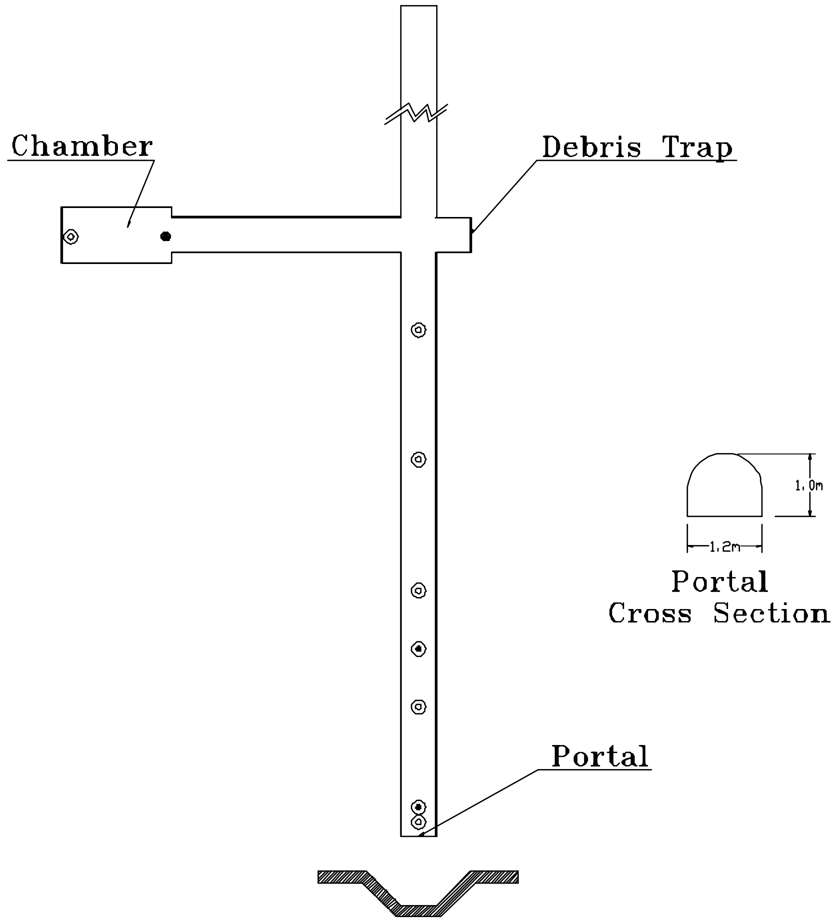


Fig. 3 Intermediate scale test magazine configuration for test No. T1C3

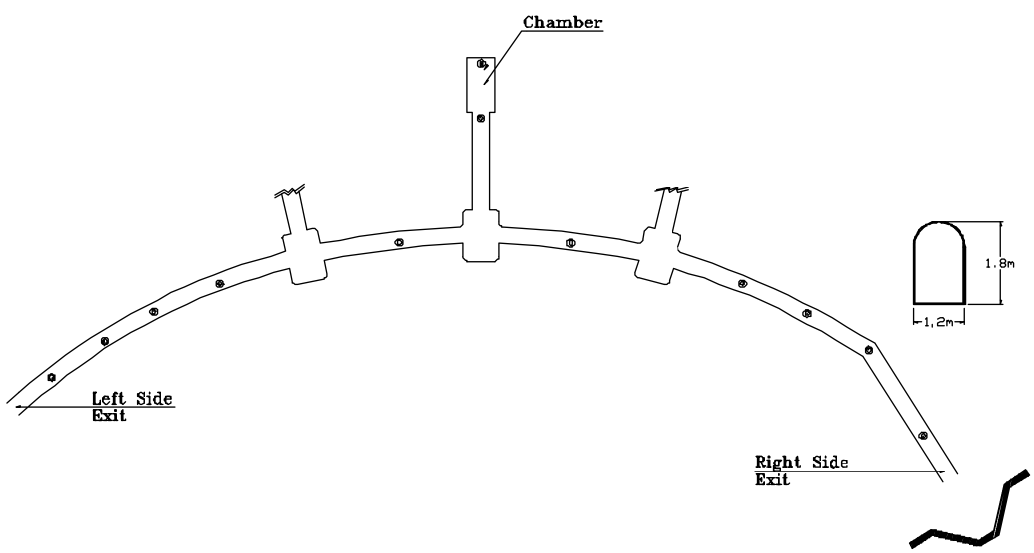
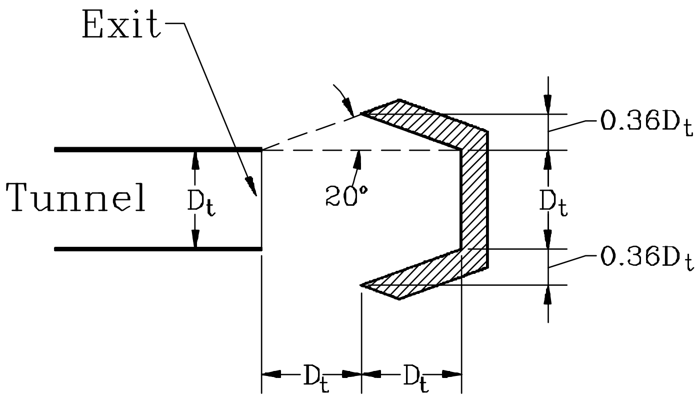


Fig. 4 Intermediate scale test magazine configuration for test No. T5C2



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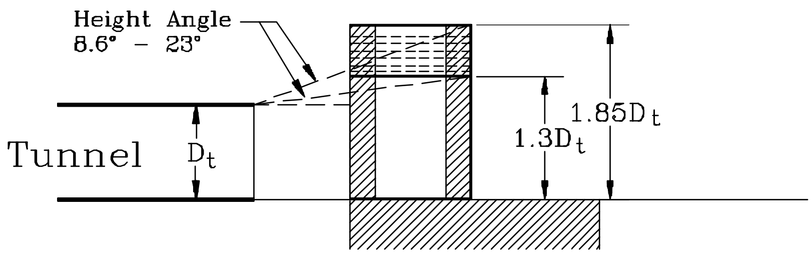
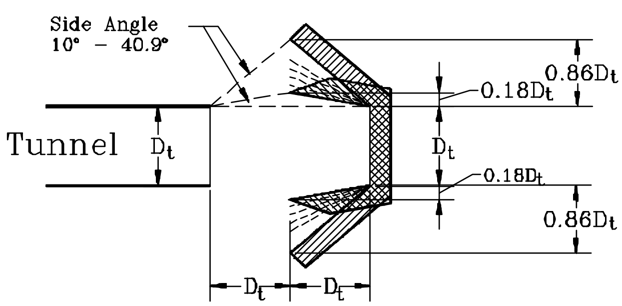


(b)

Fig. 5 Type V portal barricade for the height angle variation test



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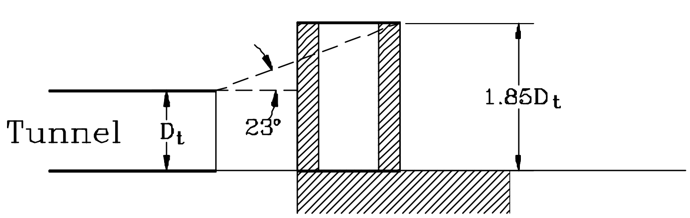

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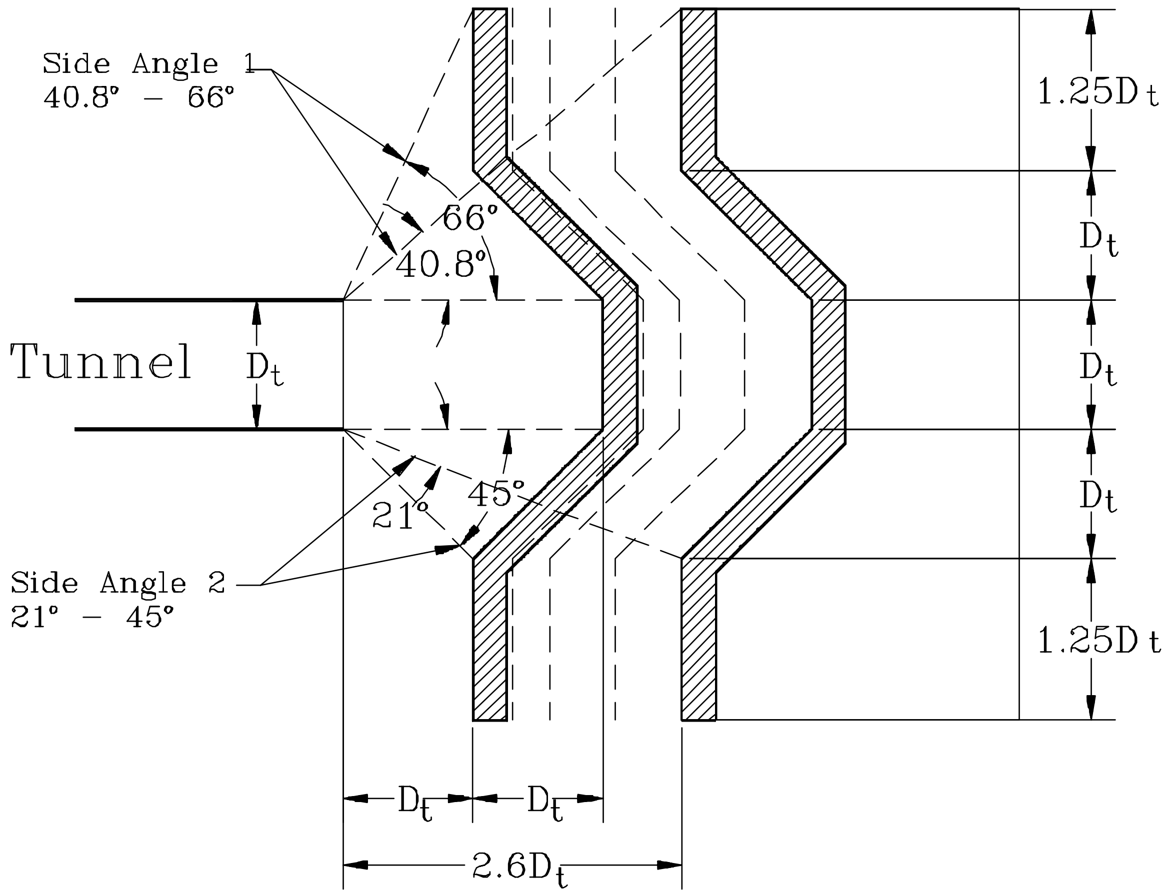
Fig. 6 Type V portal barricade for the side angle variation test



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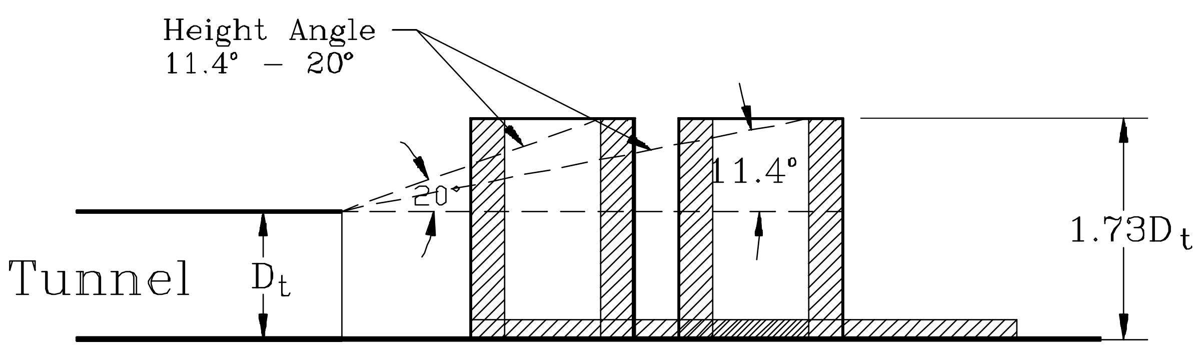


(b)

Fig. 7 Stand-off distance variation test with type I portal barricade

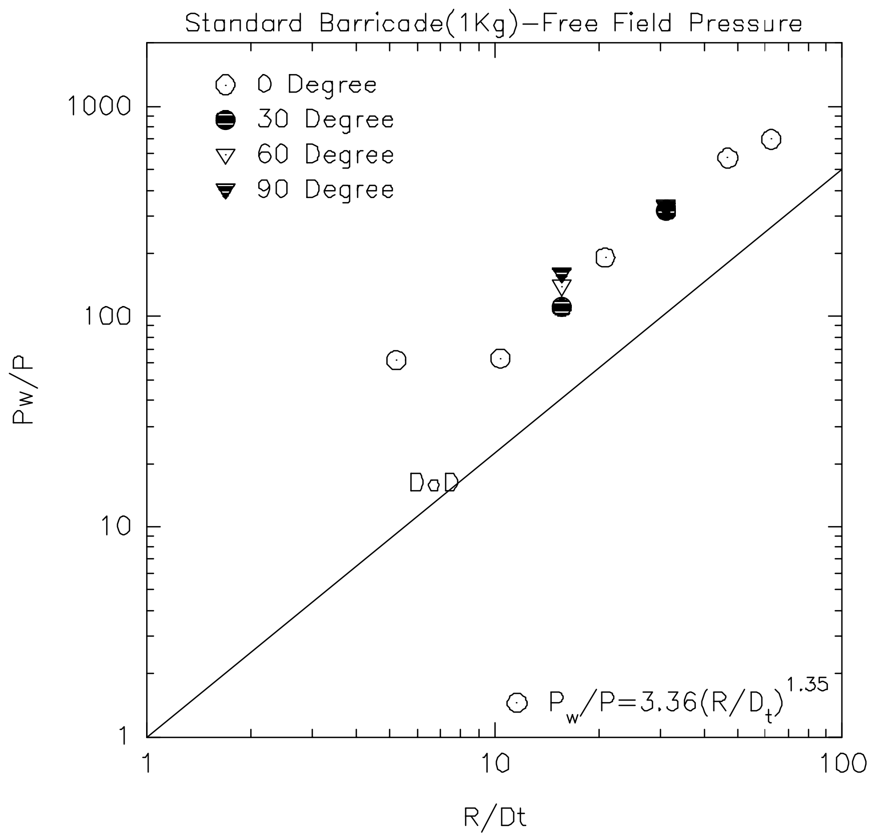
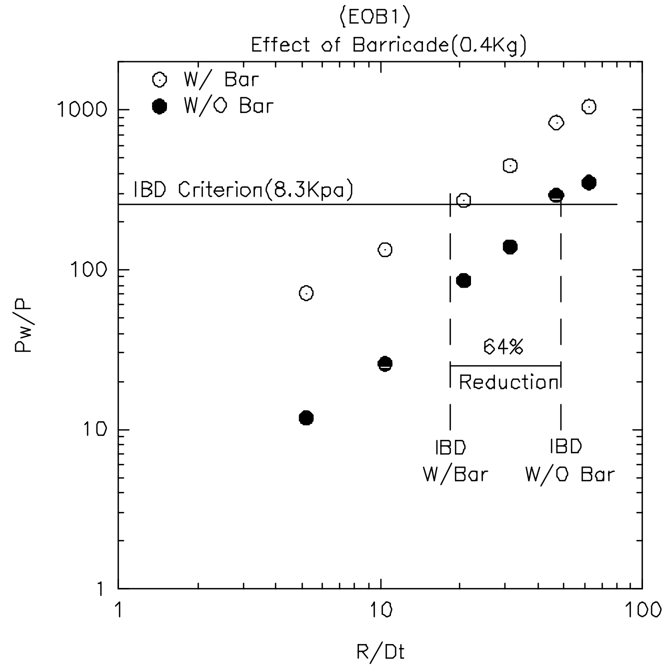


Fig. 8 Scaled pressure vs scaled distance for a small scale test with type I barricade



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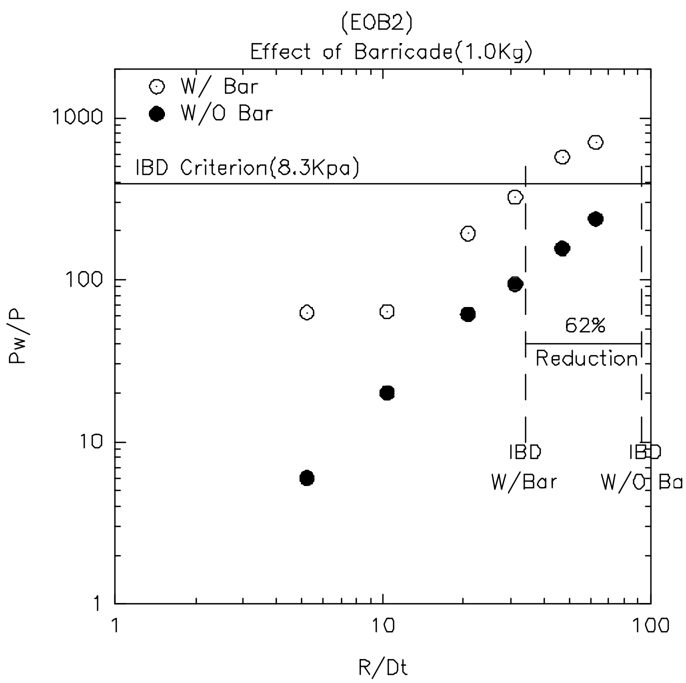
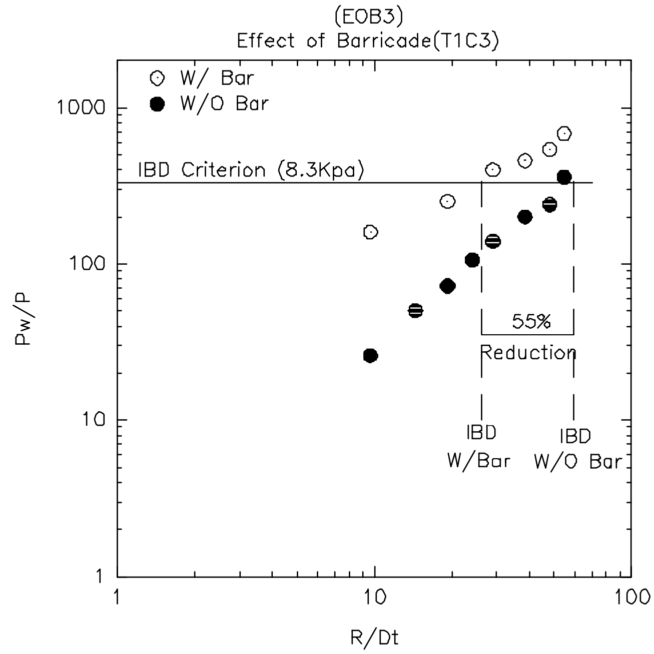


(b)

Fig. 9 IBD reduction for small test with type I portal barricade



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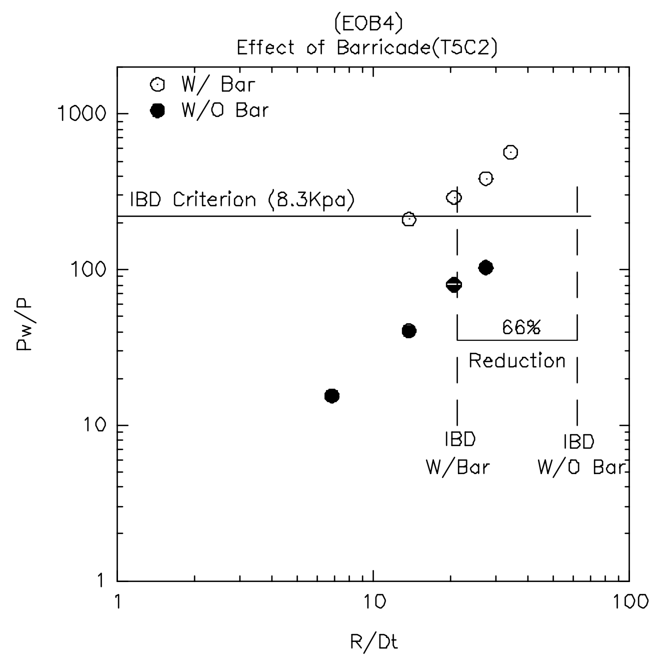

(b)

Fig. 10 IBD reduction for intermediate scale test with type I portal barricade

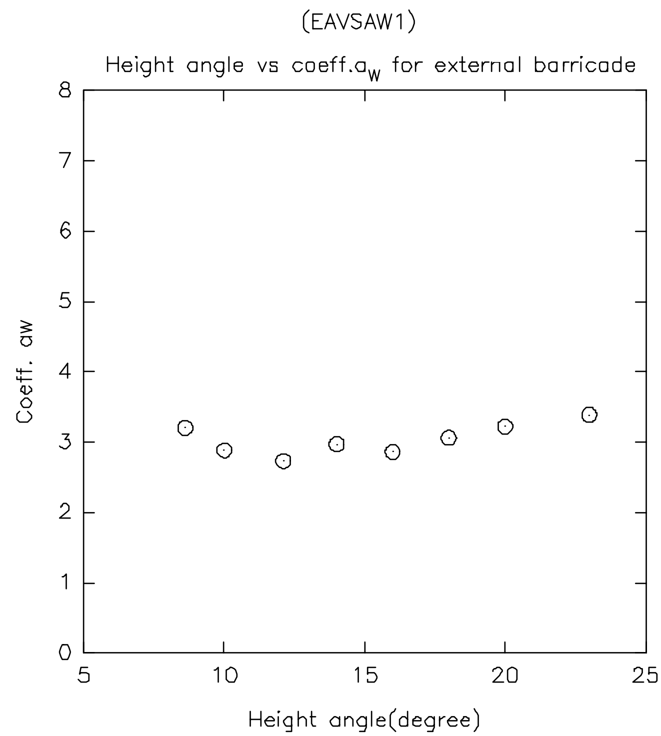

Fig. 11 Coeff. a_w vs height angle for the height angle variation test

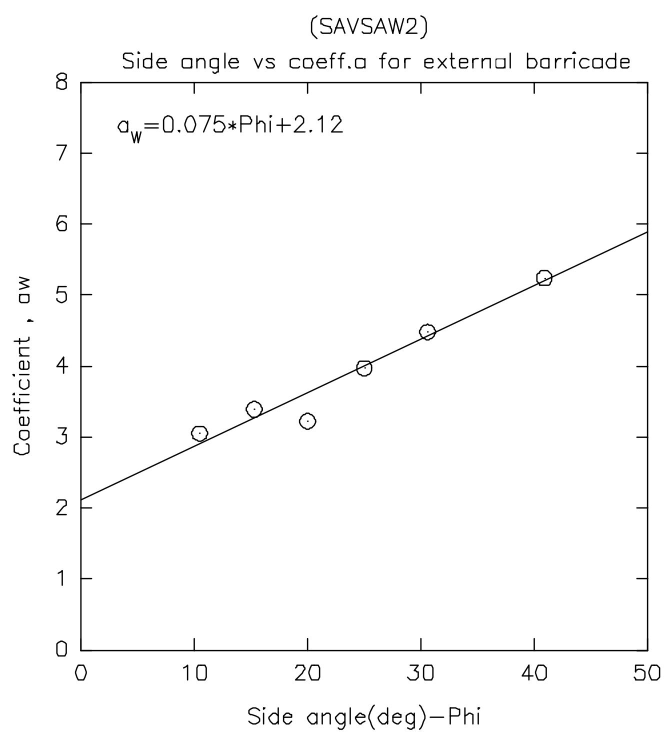

Fig. 12 Coeff. a_w vs side angle for the side angle variation test

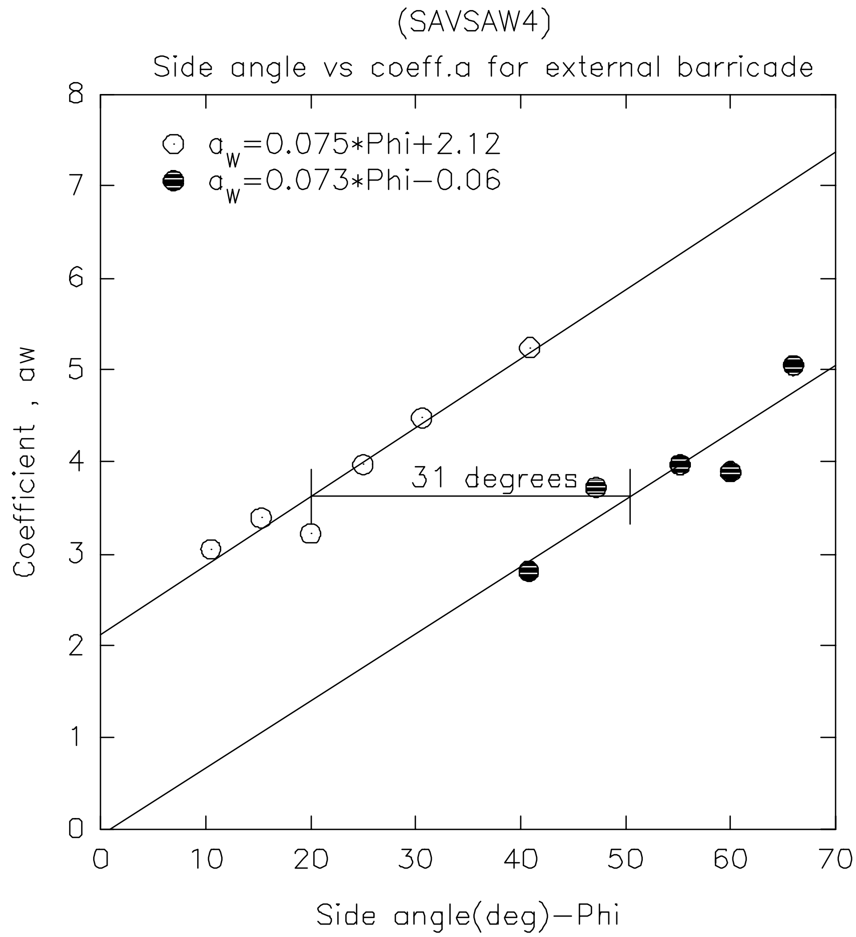

Fig. 13 Coeff. a_w vs side angle for the stand-off distance variation test